Remote Sensing of Coastal Atmosphere EM/EO Conditions

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SUMMARY
Coastal region Marine Atmospheric Boundary Layer (MABL) EM/EO properties vary dramatically over short distances, 10-30 km. The properties are affected by the vertical gradients of temperature and humidity from the surface to the top of a capping inversion. They are also affected by locally produced and advected aerosol. Remote sensing offers a desirable approach to estimate variations of the MABL, such as its depth and moisture content, which affect these properties. A multispectral approach using visible and infrared data is tested to indirectly estimate the depth of the MABL, aerosol optical depth, surface moisture, and sea-surface temperature. Remote data describe high resolution horizontal and temporal variations, important in the coastal regions, but not described by point measured data. The technique has been tested with data from recent exercises and field experiments. The technique was applied to cases off the southern California coast in August 1993 (VOCAR) and in the Arabian Gulf and Gulf of Oman in February 1995 (SHAREM 11 O), and compared to in situ measurements of the coastal MABL from aircraft, ship and shoreline stations. Limitations of the approach due to sun glint, continental aerosols and more complex MABL structures are also discussed.

1. INTRODUCTION

Knowledge of the characteristics of the marine atmospheric boundary layer (MABL) is critical to large scale investigations of air-sea interactions as well to coastal analysis and prediction. Coastal region MABL structures vary dramatically over short distances, 10-30 km. The height of the MABL is a feature of interest in several applications. For example, it is the location of elevated trapping layers affecting radio/radar waves. It is also the upper limit for mixing volume of pollution arising from shoreline activities. The depth of the MABL may be quite variable in coastal regions because it is influenced by both synoptic scales meteorological and local coastal circulations. In either case, horizontal variations occur in both the height of the MABL and strength of the capping inversion.

Conventional means of in situ measurement are necessarily limited due to the lack of vertical profile measurements over the coastal ocean. Methods using satellite atmospheric soundings are limited by the broad weighting functions resulting in poor resolution of the sharp temperature and moisture gradients at the top of the MABL. Therefore, the further development of satellite-based MABL characterization methods to estimate variations of the MABL, such as its depth and relative moisture content, are valuable both for regional and global scale studies.

This paper describes an indirect method to obtain MABL descriptions for clear regions by balancing the estimates of aerosol optical depth and the total water vapor with a relationship between relative humidity and radiative extinction. This method is referred to as the multispectral approach. The method estimates MABL height and moisture variables in the well-mixed boundary layer. First, the technique is presented followed by an evaluation during the Variability of Coastal Atmospheric Refraction (VOCAR) experiment during August/September 1993. Then results from other cases from the Persian Gulf and coastal Central California are discussed.

2. MULTISPECTRAL METHOD

The method described here relies on previously developed techniques for estimating aerosol optical depth and total column water vapor. Aerosol optical depth techniques have been developed by Refs 1, 2 and others. This study uses the red-visible radiance measurements of the NOAA AVHRR (channel 1 & 2) and their direct relation to aerosol optical depth (Ref 2). Also, several techniques have been developed to detect atmospheric water vapor variations from satellite measurements (Refs 3 and 4). The method used here follows Ref 4 that relates total column water vapor to the difference between the split window brightness temperatures from the NOAA AVHRR sensor (channel 4 and 5). Since both estimates are derived from the same sensor, the boundary layer estimates described below can be derived from a single data source.

Three assumptions about the marine boundary layer and vertical profile of extinction and water vapor are needed to relate optical depth and column water vapor to MABL depth and relative humidity. First is that the MABL is well-mixed. Second, the only significant contribution to aerosol optical depth results from extinction by aerosols in the MABL. Finally, the percentage of water vapor in the MABL can be estimated from in situ data or other satellite measurements.

Within the clear, well-mixed MABL, potential temperature and specific humidity/mixing ratio tend to be constant with height. Adiabatic mixing due to buoyancy and wind shear effects, described by Ref 5 and others, is responsible for maintaining these well-mixed profiles. Fig. 1 illustrates the evolution of a well-mixed boundary layer using a time series of ship-measured rawinsonde soundings off the Southern California coast. Note that potential temperature is nearly constant with height in the boundary layer. Mixing ratio (not shown) is also nearly constant with height in the MABL. The multispectral technique takes advantage of these simple distributions and is also based on the well-known relationships between temperature, saturation vapor density and relative humidity.

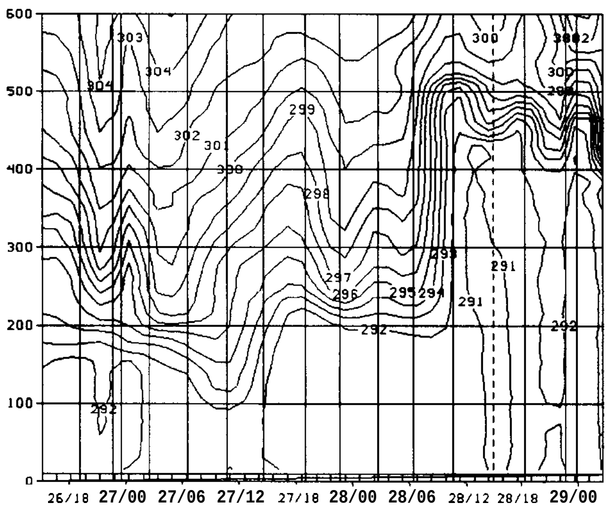

Fig. 1. Time series of MABL evolution using 17 rawinsondes off the Southern California coast, 26-29 August 1993. Contours of virtual potential temperature (K) illustrate the height (m) of the MABL.

The technique further assumes that aerosol optical depth at the red-visible and near-infrared wavelengths results from particles that are confined primarily within the MABL. If this assumption is true, then the optical depth in the red-visible would be due to the integrated effects of extinction due to these aerosols in the MABL. Ref 6 describes atmosphere aerosol distributions and concludes that for marine particles, absorption is small and the extinction is due to scattering. This extinction coefficient is a function of the cross sectional area for a given particle radius, the extinction efficiency (dependent on the complex refraction index and particle radius), and the distribution of particles by radius. Variations in each of these three factors produce corresponding changes in extinction. Ref 7 showed that the dominant term affecting extinction is particle size. Ref (2) developed a relationship between extinction and relative humidity consistent with Ref 7. This relationship is based on aircraft measurements of extinction within the MABL off the southern California coast in 1982.

Satellite estimates of optical depth and column water vapor are both related to the MABL height and moisture. An iteration method was devised to solve for the MABL height and surface relative humidity for clear regions in a satellite pass using the AVHRR data, Refs 8 and 9. Sensitivity estimates using a model atmosphere indicated the method is reliable when the MABL satisfies the assumptions of the technique, Ref 9.

3. VOCAR RESULTS

The multispectral approach has been successfully applied to MABL analyses over coastal regions of Northern California and Southern California (Ref 10 & 11) and the Persian Gulf (Ref 12). In this paper we present a validation of the technique using two cases during the Variability of Coastal Atmospheric Refractivity (VOCAR) experiment, off the southern California coast, in August-September 1993, using rawinsondes and newly available aircraft data from Naval Weapons Test Center, Point Mugu, CA. The initial VOCAR results are contained in the thesis, Ref 10, and conference presentations at the 1994 AGARD meeting, Ref 11.

To use the VOCAR period to test the technique, an estimate of the percentage of the water vapor in the MABL was used. This is an important improvement to the technique for climatological regions where significant water vapor is found above the marine inversion.

The VOCAR cases presented here were chosen because each was a clear day in the VOCAR region and rawinsondes were launched within 30 minutes of the satellite pass time at seven locations (one ship, two island, 4 coastal locations). In addition, aircraft data are now available providing low-level temperature and moisture profiles between the coast and San Nicolas (NSI) and San Clemente (NUC) islands within two hours of the satellite overpass. The aircraft flew saw-tooth vertical profiles between 75 m and 825 m, penetrating the mixed layer.

The two cases use AVHRR afternoon satellite passes on consecutive days, 26-27 August 1993. In each case, there is significant mid-tropospheric water vapor. We computed the percentage of water vapor density in the MABL, compared with the total from the surface to 400 mb, for all rawinsonde locations. The percentage, which is representative of the MABL throughout the region, is 14% for each case. These cases indicate that the multi spectral technique will work when significant amount of mid-tropospheric water vapor is present.

Fig. 2 shows the multispectral MABL depth analysis for the 23:47 UT 26 August 1993 (4:47 pm local) NOAA AVHRR satellite pass. The dark areas indicate that the pixels were over land, are clouds, or the iterative method did not converge at that point. The rawinsonde observations are indicated by yellow dots on the image while aircraft profiles are denoted by white dots.

Fig. 2 also shows the slope of the MABL, from shallow values to the West (75 m) to deeper values along the eastern portion of the coastal region (225 to 275 m). The thicker MABL region is associated with warmer sea surface temperatures (SST) along the California coast from Point Vincente (PVN) to North Island (NZY) near San Diego. The range of SST is from 23 to 24 C in the warmer area to 16 to 18 C south of Point Arguello (PDR) along the eastern edge of the California Current.

Rawinsonde and aircraft data confirm the coastal MABL and SST structure indicated by the mulispectral technique. The only overwater rawinsondes are from the R/V Point Sur (PSUR). Data from one rawinsonde launched during the aircraft flight, 26/2242 UT (3:42 pm), and another launched at 2332 UT (4:32 pm), near the AVHRR satellite overpass time, are used to compare with the multispectral estimates of MABL depth. The rawinsonde measured MABL depths of 152 m and 148 m compare favorably with the shallow 127 m satellite estimate.

Fig. 3 shows the multispectral MABL depth analysis for the 23:34 UT 27 August 1993 (4:34 pm local) NOAA AVHRR satellite pass. Thin stratus clouds developed to the west of San Nicholas Island (NSI), with cloud patches north and east, which reduced the clear area for the multispectral technique. In this case, the MABL depth is significantly deeper (30-65 meters) than the previous afternoon, again with a west-to-east slope of the MABL. Two Point Sur rawinsondes and the aircraft data confirmed a 25-65 meter deeper MABL at points along nearly coincident aircraft tracks as flown the previous day.

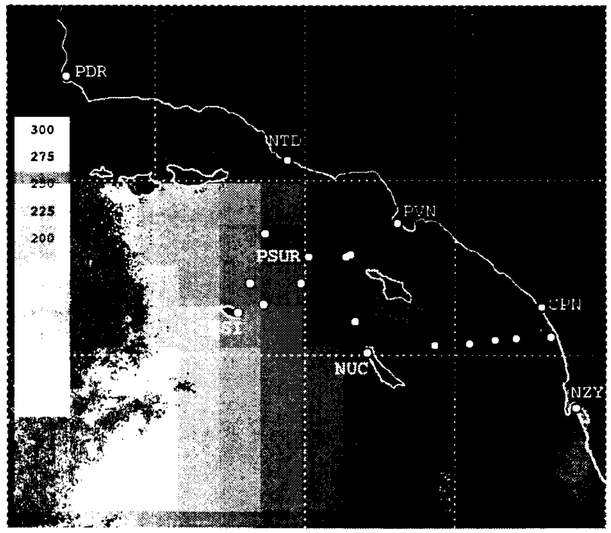

Fig. 2. Multispectral MABL depth (m) for 23:47 UT 26 August 1993 NOAA AVHRR satellite pass. VOCAR rawinsonde observations are devoted by yellow dots and aircraft profiles are given by white dots. The dark areas indicate the pixels were over land, are clouds, or the iterative method did not converge at that point.

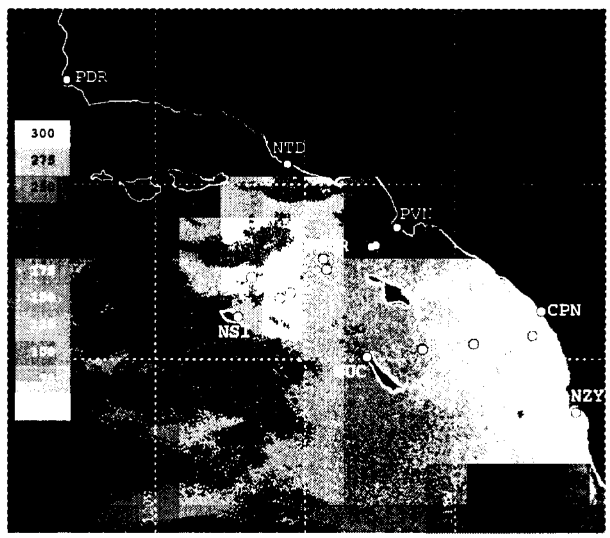

Fig. 3. As in Fig. 2, Multispectral MABL depth (m) for 23:34 UT 27 August 1993 NOAA AVHRR satellite pass. The dark areas of nonconvergence are due to the thin stratus clouds over the area west of NSI, with cloud patches to the north and east.

For statistical analysis, we compared the Point Sur rawinsondes and aircraft measurements of MABL height and virtual potential temperature at the locations indicated in Figs. 2 and 3 with the corresponding multispectral MABL height and SST estimates for each case. Combining the cases, we have 24 data points for analysis. Fig. 4 is a scatterplot of measured MABL height versus satellite estimates of MABL height. Similarly, Fig. 5 compares the virtual potential temperature from rawinsonde and aircraft data with satellite-derived SST. The statistical information is presented in Tables 1 and 2.

Two 26 August aircraft soundings in the lee of San Nicolas Island (NSI) were excluded from the analysis because the MABL appears influenced by local island effects. Aircraft soundings on 27 August were excluded if there was evidence of thin stratus clouds in the vicinity of the sounding.

For both cases, the aircraft soundings confirm the distinct gradient in MABL height and SST between San Clemente Island (NUC) and San Diego (NZY). The satellite data underestimates the depth by 40 m, but the RMS differences are less than 46 m. The aircraft virtual potential temperatures of the mixed layer fall within 1.3C of the satellite-derived SST.

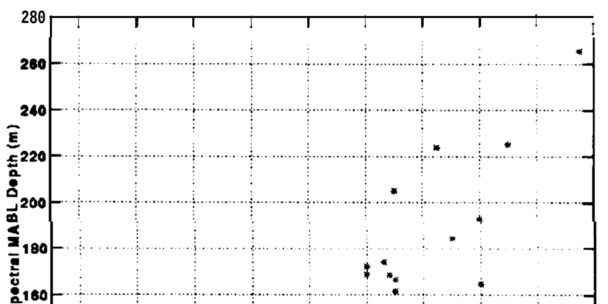

Fig. 4. ScatterPlot of aircraft and rawinsonde measured and multispectral satellite estimates of MABL depths (m).

Table 1.
Comparison of Aircraft versus Multispectral MABL Height

BIAS	39.7 m
RMS differences	45.6 m
Correlation Coefficient	.816

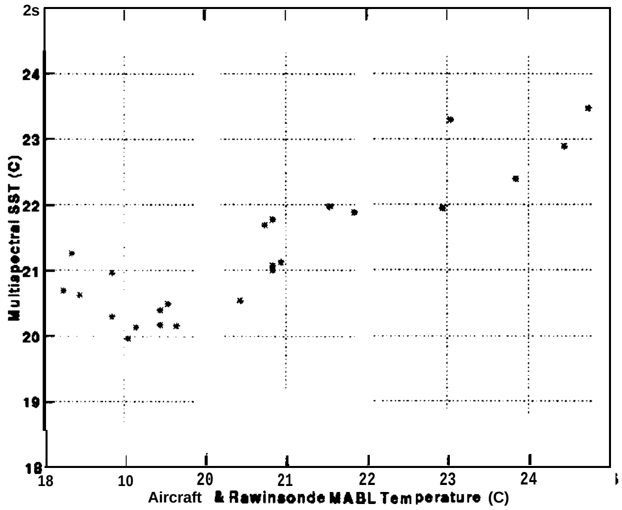

Fig. 5. Scatterplot of aircraft and rawinsonde MABL virtual potential temperature (C) and satellite estimates of SST (C).

Table 2.
Comparison of Aircraft MABL Temperature versus Satellite SST

BIAS	-0.59 c
RMS differences	1.29 C
Correlation Coefficient	0.877

4. OTHER VALIDATION CASES AND METHOD LIMITATIONS

The multispectral technique has been applied to several other coastal data sets (Ref 12). The results from these cases are summarized here and presented in more detail at the conference.

The SHAREM 110 exercise was held in the Persian Gulf and Gulf of Oman during the period of 6 to 18 February 1995. Rawinsondes were available from three ships during the entire period while aircraft data were available on five days. Due to the geography of the Persian Gulf, the atmosphere is never completely free from land influences. However, a Shamel occurred during the experiment with a period of moderate northwest winds from the Northwest along the axis of the Gulf. This flow with a long overwater fetch satisfied the conditions of the technique. A deep well-mixed MABL developed during this period (10 February). The MABL depth was measured to be approximately 1000 meters with most (83%) of the column water vapor in the MABL.

Table 3 presents an evaluation for this case from soundings from the USS David R. Ray and USNS Silas Bent. The difference between the sounding and satellite estimate was near 50 meters and the boundary layer slope was correctly determined by the satellite analysis. The satellite MABL analyses also was consistent with the cloud top temperature of some boundary layer cumulus over the western part of the Gulf. The multispectral technique proved to be very successful in this case even with considerably thicker MABLs than observed in VOCAR.

Table 3
MABL Height Comparisons for the Persian Gulf
10 February 1995

	D.R. Ray	Silas Bent
Multispectral	I 005 m	1042 m
Rawinsonde	1055 m	1090 m
Difference	50 m	48 m

Other SHAREM and coastal California cases illustrate limitations to the approach. These limitations are sun glint, continental aerosols and more complex MABL structures. With polar-orbiting sun synchronous satellites, sun glint can be a major difficulty. In conducting these validation studies, approximately 30% of the clear (otherwise usable) passes can not be analyzed because of the solar reflection from the sea surface. This problem may occur less frequently when using data from the new US NOAA geostationary satellites, GOES-8 and 9.

In one of the SHAREM cases, strong off-shore continental flow with significant dust caused plumes of elevated optical depth. The multispectral technique did converge in this case and produced MABL analyses. However, the MABL depth was hundreds of the meters in error due to the continental influences present. This case illustrates that situations with significant off-shore transport of aerosols need to examined closely. The plume-type structure of the optical depth and MABL height analyses give strong indications of the impact of the continental aerosols.

Finally, cases with multiple mixed layer structure and elevated trapping layers have been found. This is particularly common over regions undergoing cold upwelling events along the west coast of continents. Here a new mixed layer is formed over the cold water, distinctly colder than the mixed layer above it. In these situations, the multispectral approach does successful map the lower mixed layer, but does not provide any information about the inversion structure above the lowest mixed layer. In these cases, the technique can not provide any information about elevated inversions or refractive layers that are not associated with the surface but may be tactically relevant to electromagnetic-electro-optical propagation and other applications.

5. CONCLUSIONS

We have described the evaluation of remotely sensed estimates of mixed layer structure at and above the ocean surface in coastal regions using aircraft data during VOCAR and from other field experiments. Both successful and unsuccessful cases have been studied. The multispectral approach has accurately mapped the topography of the MABL, SST and optical depth conditions for cases from coastal Southern California, Persian Gulf and Central California coast. The comparisons with aircraft and rawinsondes show the satellite data to correctly describe the MABL topography and agree to within 20% with in situ observations. The method can be applied to all cases of clear skies. However, sun glint, continental aerosols and situations with complex MABL structures can not be analyzed with this approach using polar-orbiting satellite data. The sun glint problem should occur less frequently with the new US geostationary satellites. Future studies will evaluate this source of multispectral data for MABL studies.

6. ACKNOWLEDGMENTS

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